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**The Characterization of Spinal Compression
in Various-Sized Human and Manikin
Subjects During +Gz Impact**

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**Biosciences and Protection Division
Human Effectiveness Directorate**

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**Air Force Research Laboratory
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The Characterization of Spinal Compression in Various-Sized Human and Manikin Subjects during +Gz Impact

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ABSTRACT

Background: During +Gz impacts such as those encountered during ejection, the human torso and spine compress or slump due to the inertial forces acting on the body. Spinal compression can be characterized by a second-order differential equation involving coefficients such as damping ratio, natural frequency and spring constant. *Objective:* To characterize spinal compression resulting from +Gz impacts and determine how well test manikins replicate responses of similar size humans. *Methods:* Various-sized humans were tested with identical conditions on a vertical deceleration tower. Seat and chest accelerations were used to calculate the damping ratio, natural frequency and spring constant of each subject. Data analysis was performed to determine what correlations may exist between spinal compression and sitting height, torso mass, gender or vibration parameters. *Results:* Results show that spinal compression had no significant correlation to sitting height, torso mass, gender, damping ratio, undamped natural frequency or spring constant. Estimated 5th, 50th, and 95th percentiles of spinal compression were 1.1", 1.7", and 2.5" for the Vertical Impact Protection seat and 2.4", 2.8", and 3.6" for the ACES II seat. The Large JPATS, Large ADAM and LOIS manikins were found to align closely with human spinal compression.

INTRODUCTION

During an in-flight emergency, the crew is often faced with very little time to decide to eject from an ailing aircraft. In many aircraft, once the crewmember pulls the ejection handle, the aircraft canopy needs to be jettisoned prior to the ejection. At high sink rates or adverse attitudes, the few tenths of a second required for the

canopy to clear the aircraft could be the difference between life and death. For this reason, many combat aircraft including the F-35 Joint Strike Fighter are utilizing a through-the-canopy approach. As the crewmember initiates the ejection by pulling the handle, a sequencing system sends a signal to a Transparency Removal System (TRS) or a canopy fragilization system that either cuts or weakens the transparency material and allows the seat with supplemental transparency penetrators to pass through the canopy. This results in reducing the ejection time by up to 300 milliseconds. Many combat aircraft also have a backup mode which allows the seat to penetrate the transparency even if the canopy fails to jettison or if the TRS or fragilization systems happen to fail. One of the disadvantages of going through the transparency is that a tall crewmember's head may hit the transparency prior to the seat transparency penetrators, thereby possibly causing head/neck injuries to the crewmember. Ejection seat tests are conducted with test manikins to determine if the escape systems are safe. However, ejection seats are tested with only a few size manikins, and human responses are often different than manikin responses. The objective of this study was to determine the degree of human slump, or vertical compression, during an ejection, and to determine a correlation between subject anthropometry (e.g. sitting height, upper body mass, etc.) and how much they slump. This study also examined the differences between human and manikin slump and the differences in slump for tests conducted using a generic research seat and an actual ejection seat.

METHODS

Data analysis was performed from an approved IRB 1999 study¹ involving tests that were

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conducted on the Air Force Research Laboratory's Vertical Deceleration Tower (VDT; Figure 1) using a generic Vertical Impact Protection (VIP) seat that was mounted to the carriage. The carriage and seat were released and a +Gz acceleration pulse was generated when the plunger, mounted on the back of the carriage, entered the hydraulic decelerator.

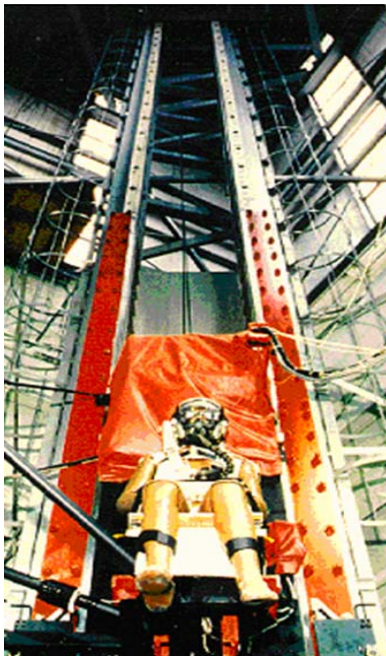


Figure 1. Vertical Deceleration Tower (VDT)

This study had 40 human subjects (23 male; 17 female) of various weight and height that were tested three times under identical conditions at seat accelerations of +10 Gz.² The positions of the headrest and seat back were directly aligned with the seat acceleration, and the seat pan was aligned perpendicular to the seat back. The subjects wore a standard HGU-55/P helmet and were confined to the seat by a MB-6 double shoulder harness and lap belt (Figure 2).² During vertical deceleration, various body displacements, such as the chest and head, were measured by the SELSPOT Motion Analysis System which consists of two on-board cameras that capture 500 samples per second.²



Figure 2. 1999 Study with Vertical Impact Protection (VIP) Seat

Vertical displacements of the chest for each test were then compiled in the Air Force Research Laboratory's Biodynamics Data Bank, as well as the subject's sitting height, total body mass and gender. Sitting height was measured as the vertical distance from the sitting surface to the top of the head. Variables such as torso mass and vibration parameters were determined from 23 subjects (12 male; 11 female) out of a total of 40 subjects from the 1999 study. The selection process of these 23 subjects was based on a representative sample for a total body mass distribution. Torso mass was then estimated by the Generator of Body Data (GEBOD) computer model, which incorporates 32 anthropometric measurements to determine the mass.³ Next, the subject's vibration parameters were determined by modeling the compression of the human spine as a second-order differential equation shown in Equation 1.^{4,5,6}

$$-\frac{d^2 z}{dt^2} = \frac{d^2 \delta}{dt^2} + 2\zeta\omega_n \frac{d\delta}{dt} + \omega_n^2 \delta \quad (1)$$

where:

$$\frac{d^2 z}{dt^2} \quad \text{seat acceleration as a function of time}$$

δ	deflection of the body mass with respect to the seat (in)
ω_n	undamped natural frequency (rad/s)
ζ	damping ratio
$\frac{d^2 \delta}{dt^2}$	chest acceleration as a function of time relative acceleration of the mass with respect to the seat

Equation 1 was used to determine different combinations of ω_n and ζ with the aid of an in-house computer integration program that

required input parameters of $\frac{d^2 z}{dt^2}$ and $\frac{d^2 \delta}{dt^2}$.

Figure 3 illustrates the program's output of the actual mass acceleration response

$\left(\frac{d^2 z}{dt^2} + \frac{d^2 \delta}{dt^2} \right)$ and the computed mass

acceleration response for a given ω_n and ζ . Final values of ω_n and ζ were determined from the best fit computation using the method of least squares.

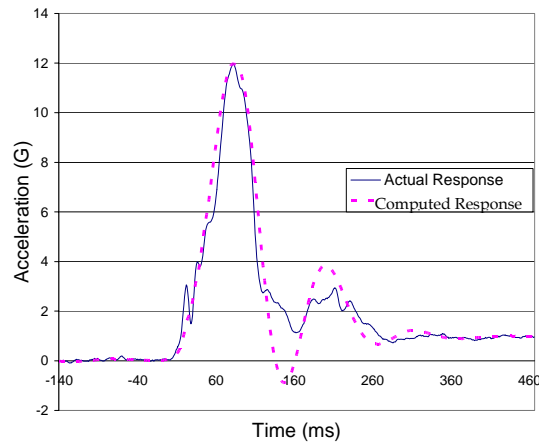


Figure 3. Model and Empirical Acceleration Response

The last vibration parameter calculated was the spring constant, as shown from Equation 2.⁷

$$k = \omega_n^2 \times m \quad (2)$$

where:

k spring constant of the body (lb_f/ft)
 m mass of torso (lb_f*s²/ft)

Statistical analysis was performed by Simple Linear Regression to determine whether maximum z displacement correlated with gender, height, mass, natural frequency, damping ratio, or spring constant. The Weibull Cumulative Distribution was used to fit the sample cumulative proportions to determine estimated 5th, 50th, and 95th percentile chest displacements for human subjects during a +Gz acceleration impact.

Since manikins were not tested during the 1999 study, a separate analysis was used to compare the impact responses between humans and manikins. Data were gathered from the Biodynamics Data Bank on an approved IRB 2004 study.¹ Thirteen human subjects (9 male and 4 female) and three manikins (Large JPATS, ADAM and LOIS) were identically tested in a VDT at +10 Gz. The test conditions consisted of an ACES II F-16 ejection seat, PCU-15P or PCU-16/P harness, HBU lab belt, and HGU-55/P flight helmet. The seat back and headrest were aligned with the vertical acceleration, and the seat pan was positioned perpendicular to the seat back, as shown in Figure 4. Chest displacement data were collected from a Weinberger Motion Analysis System that consists of 2 cameras capturing 11 positioned targets at 500 samples per second.



Figure 4. 2004 Study with ACES II Seat

From these data, the Weibull Cumulative Distribution was utilized to fit the sample

cumulative proportions to determine estimated 5th, 50th, and 95th percentile for chest displacement of the human population. This distribution then served as a comparison for the Large JPATS, ADAM and LOIS manikin chest displacement.

RESULTS

The Simple Linear Regression method⁸ was used to determine which individual variables may have influence on spinal compression (maximum z-chest displacement). Out of the 40 subjects exposed to +Gz impact in the VIP seat, variables from 23 subjects (12 male and 11 female) were collected or calculated. These variables included torso mass, damping ratio, damping frequency, spring constant and the average maximum chest displacement. Figure 5 was plotted with chest displacement versus the subjects' sitting height, and showed no correlation, with $p=0.67$ and $p=0.50$, for male and female respectively. Likewise, Figure 6 shows no correlation for chest displacement versus the subjects' torso mass with $p=0.32$ for male and $p=0.61$ for female.

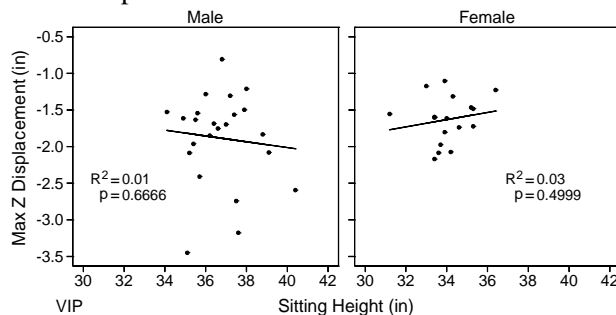


Figure 5. Maximum Chest Displacement versus a Subject's Sitting Height

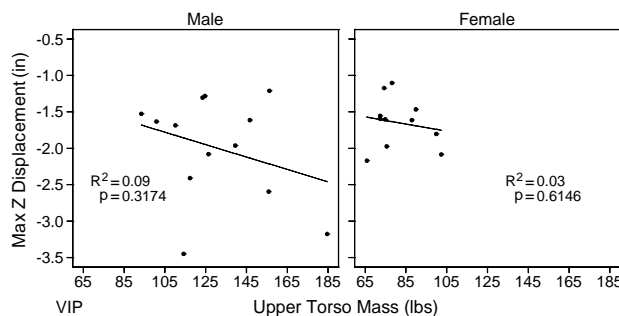


Figure 6. Maximum Chest Displacement versus a Subject's Torso Mass

Figure 7 contains a bubble plot for the maximum z chest displacement in the VIP seat illustrated by bubbles with the sitting height in the y-axis and the torso mass in the x-axis. The size of the bubble indicates absolute chest displacement, with the largest circle having the greatest z displacement and the smallest circle having the least z displacement.

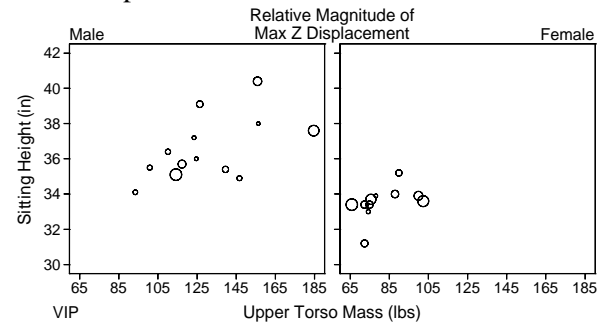


Figure 7. Plot of Sitting Height and Torso Mass versus Maximum Chest Displacement

There was no correlation found for the damping ratio ($p=0.50$ male; $p=0.41$ female; Figure 8), spring constant ($p=0.81$ male; $p=0.76$; Figure 9), or the damping frequency ($p=0.47$ male; $p=0.56$ female; Figure 10) with chest displacement as the independent variable.

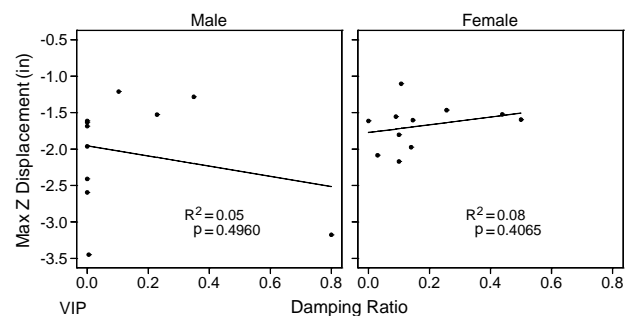


Figure 8 Plot of Damping Ratio versus Maximum Chest Displacement

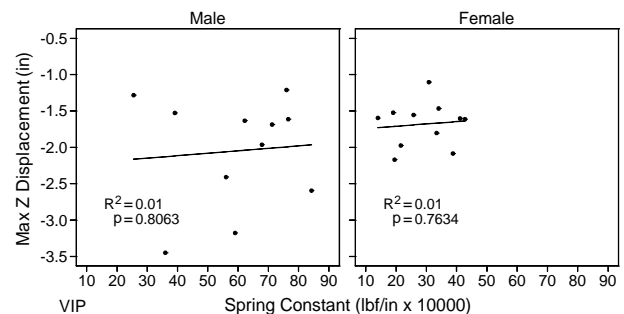


Figure 9 Plot of Spring Constant versus Maximum Chest Displacement

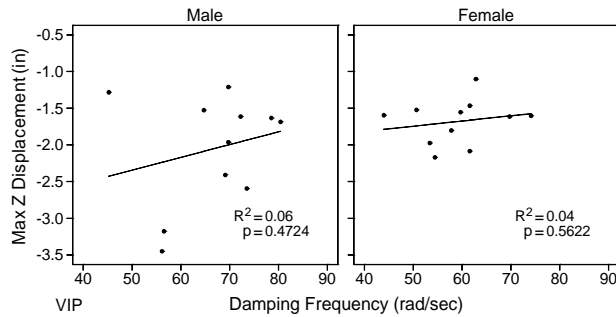


Figure 10. Maximum Chest Displacement versus a Subject's Damping Frequency

A two-tailed two-sample t-test⁸ did not find a significant difference in the maximum z displacement of males vs. females for the VIP seat (means: male = -1.9 in, female = -1.6 in, $p = 0.14$). Although chest displacement did not correlate with either mass or height, a second test was performed to evaluate genders of the same size. An Analysis of Covariance⁸ was used to compare genders at the average sitting height and torso mass across all subjects. Similarly, no significant difference was found in gender (means: male = -1.8 in, female = -1.9 in, $p = 0.94$).

The Weibull Cumulative Distribution was used to fit the sample cumulative proportions of maximum spinal compression for the VIP seat (Figure 11; Table 1) and ACES II seat (Figure 12; Table 1) with minimum and maximum values from the sample data. Two displacement values for the VIP seat (-3.5 and -3.2 in) and ACES II seat (-3.9 and -1.6 in) were discarded because these points did not fit the general populated trend.⁸

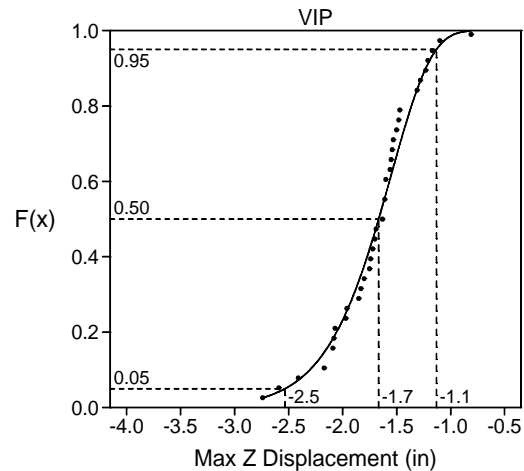


Figure 11. Weibull Fit of Sample Cumulative Proportions of Maximum Chest Displacement Using the VIP Seat. (N=40)

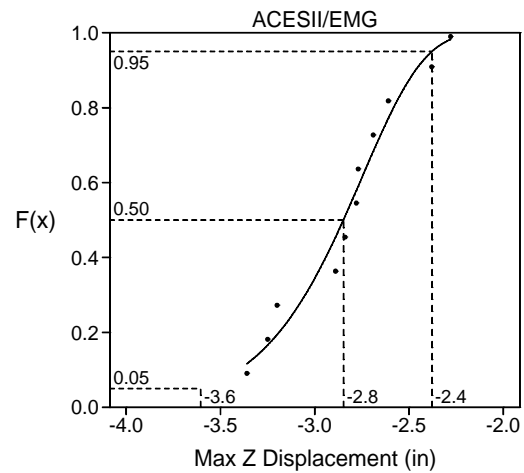


Figure 12. Weibull Fit of Sample Cumulative Proportions of Maximum Chest Displacement Using the ACESII Seat (N=13)

Table 1. The Chest Displacement Range for VIP and ACES II Seats

	VIP Chest Displacement (in)	ACES II Chest Displacement (in)
Min	-0.8	-1.6
5%	-1.1	-2.4
50%	-1.7	-2.8
95%	-2.5	-3.6
Max	-3.4	-3.9

Last, the ADAM, Large JPATS, and LOIS manikins respectively exhibited maximum chest displacements of -3.8in., -2.7in., and -1.5

inches, respectively, when exposed to +Gz acceleration impact tests in the ACES II seat (Table 2).

Table 2. The Average Maximum Chest Displacement of Manikins During +10Gz Impact

Manikin	Chest Displacement (in)
Large JPATS	-2.7
ADAM	-3.8
LOIS	-1.5

DISCUSSION

Statistical results concluded that spinal compression did not correlate with the subject's height, torso mass, or gender. Likewise, no significant relationship was found between the vibration parameters (ω_n , k and ζ) and compression of the spine.

When comparing VIP and ACES II seat chest displacement, there was a significant difference that resulted in a p-value of 0.0001. One obvious reason for there to be a significant difference was the difference in the seat structures. While the VIP seat was a flat wooden seat mounted on an aluminum fixture with no seat cushion, the ACES II seat was an aluminum structure with a fiberglass seat pan and a seat cushion that was comprised of layered poly foam, temper foam and space fabric. As a result, greater vertical displacement was expected to occur during impact with the ACES II seat due to the flexion of the fiberglass seat pan and cushion.

Humans tested in the VIP seat showed a displacement of -2.5, -1.7 and -1.1 inches for the 5th, 50th and 95th cumulative percentages respectively. Human tested in the ACES II seat had greater chest displacement values of -3.6, -2.8 and -2.4 inches for the 5th, 50th and 95th cumulative percentages respectively. To ensure manikins were representative of humans, manikins were also tested in the ACES II seat during +10Gz impact tests. The manikin with the smallest displacement was the LOIS manikin which had a chest compression of -1.5 inches in the vertical direction. The JPATS manikin had

an average displacement of -2.7 inches. The ADAM manikin had the largest displacement (-3.8 inches) relative to the other manikins and humans.

CONCLUSIONS

In conclusion, absolute vertical displacement of the spine was found to be dependent on the selected seat structure. However, vertical displacement due to spinal compression was found to be unpredictable among subjects. It is recommended that further analysis be conducted to characterize compression of the spine utilizing other parameters such as back strength or posture. In the end, LOIS, Large JPATS and Large ADAM manikins were found to display a human range of spinal compression.

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BIOGRAPHIES

Erin Caldwell is a biomedical engineer who is supported by an appointment of the Research Participation Program at the Biomechanics Branch, Human Effectiveness Directorate, Air Force Research Laboratory, Wright Patterson AFB, administered by the Oak Ridge Institute for Science and Education through an interagency agreement between the U.S. Department of Energy and AFRL/HEP.

John Plaga is research aerospace engineer who has been with the Biomechanics Branch of the Human Effectiveness Directorate, Air Force Research Laboratory, for 16 years. He has been involved in escape system research since his graduation from The Ohio State University in 1989. His research projects have included flow stagnation concepts, windblast deflection studies, biomechanics of helmet-mounted displays, development of ejection seat instrumentation systems, studies of ejection seat dynamics, investigation of the Russian K-36 ejection seat, investigation of the implications of